Acoustic Propagation in Continental Shelf Break and Slope Environments

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LONG-TERM GOALS

The long-term goal of the research is to increase the physical understanding of acoustic propagation in continental shelf and slope environments in the 25-5000 Hz band. This includes both the physics of the seabed and the coupling to physical mechanisms in the water column in complex range- and azimuth-dependent littoral waveguides.

OBJECTIVES

There were two main objectives of the current research. The first objective was to complete a final numerical implementation of a statistical inference approach based on a maximum entropy formalism. The second objective was to combine the waveguide parameter statistical inferences with geophysical data from the Shallow Water 2006 (SW06) experiment on the New Jersey continental shelf to model range-dependent acoustic data for the purpose of determining the bandwidth and range over which the effects of range-dependent inhomogenities in the sub bottom layering can be discerned.

APPROACH

The approach applied in this work was to continue to use data obtained from the SW06 experiment to test hypotheses made for statistical inference of waveguide parameters and the effects of sub bottom seabed layering on low frequency acoustic propagation. Further, there is ongoing collaboration between Mr. Jason Sagers, my graduate student, and I on (1) identifying mode coupling effects in SW06 data and (2) performing statistical inference in environments with significant horizontal variability.

The theoretical approach to statistical inference is based on maximum entropy. The main advancement made by the current work is the discovery of how to specify the average error constraint for maximization of the Shannon entropy.[1] Previously, all statistical inference methods in ocean

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acoustics have assumed a Bayesian methodology. Currently, for the problems investigated, it has been found that Monte Carlo integration (around a million samples) over the nuisance parameters suffices to generate marginal probability distributions for waveguide parameter values.

The numerical approach to investigating the effects of sub bottom layering on broadband propagation is to compute the broadband response with a parabolic equation algorithm for the case where the details of the range-dependent sub bottom layering are properly taken into consideration. In the analyses good agreement between modeled and measured data has been achieved. One then compares the fully range-dependent simulated field to the case where the sub bottom layering is horizontally stratified. A comparison between the simulated fields gives information on the bandwidth and source-receiver ranges where effects due to the sub-bottom layering in the time series are discernable.

WORK COMPLETED

The work completed in FY10 includes (1) the completion of the development of a numerical implementation of a maximum entropy methodology to quantify waveguide and source parameter statistics and (2) quantifying the bandwidth and source-receiver range over which there exist discernable effects of sub bottom layering on broadband propagation in shallow water.

(1) Waveguide statistics: A posterior probability distribution suitable for estimating the statistical properties of ocean seabed parameter values inferred from acoustic measurements was derived from a maximum entropy principle. The specification of a second-order expectation value constrains the maximization of the relative Shannon entropy functional. This constraint determines the sensitivity of the resulting posterior distribution, which has the canonical form. From the posterior distribution, probability distributions for individual parameter values can be determined from integration over the other parameters. The approach is an alternative to deriving a likelihood function assuming Gaussian statistics for the noise and model mismatch and then applying Bayes' formula to obtain the posterior distribution. The expectation value that specifies the constraint is determined from the value of the mismatch for the model solutions obtained for multiple data sets. The method was applied to ocean acoustic measurements taken on the New Jersey continental shelf where the seabed is comprised of coarse sand. Data from four measurements were interpreted as samples from a data ensemble with the same statistical properties and were used to specify the expectation value in the maximum entropy constraint.

(2) Effect of sub bottom layering: Examined were the effects of range inhomogeneities in the seabed layering on low frequency broadband sound propagation. Acoustic measurements generated by an impulsive sound source were made on the New Jersey continental shelf over propagation paths where previous geophysical analyses provide information on the seabed layering structure. Additional information on the physical properties of the sediment layers, such as sound speed and attenuation, was obtained from previous inversions of acoustic data. The seismic and the geophysical information, the inferred geoacoustic information for the sediment layers, and sparse water column sound speed measurements provided inputs for a finite element parabolic equation propagation model. With this information modeled time series were produced and were compared in the 35-265 Hz band to the measured received times series from impulsive sources deployed at ranges between about 70 and 350 water depths. Further, simulations of the received time series were performed for each of the propagation paths using modified sub-bottom layering structures for the purpose of quantifying the acoustic field effects associated with deviations of the seabed structure from horizontal stratification.

RESULTS

(1) Waveguide statistics

Figure 1 shows the geographical location of the array and portions of three tracks during the recorded data segments that were selected for processing. The geographical positions of the tracks were deduced from measurements by a Global Positioning System (GPS). For each track the R/V KNORR traveled outwards from the horizontal line array (HLA) along the 72 meter depth contour approximately at broadside to the HLA. On each traversal the motion of the R/V KNORR was approximately uniform with an average speed of about 2.6 m/s relative to the receiving acoustical array. The portions of the three tracks during the processed data segments are nearly identical which also means that the sound propagated to the array along essentially identical paths in the 2-D range-depth plane. Thus, the sound on its way to the array from each position on the tracks, interacted with essentially the same section of the seabed in the experimental region. This is an important part of how data samples are selected that belong to *the same statistical population*. It was assumed that the spatial statistical properties of the seabed are independent of time over the duration of the measurements (about 2 days).

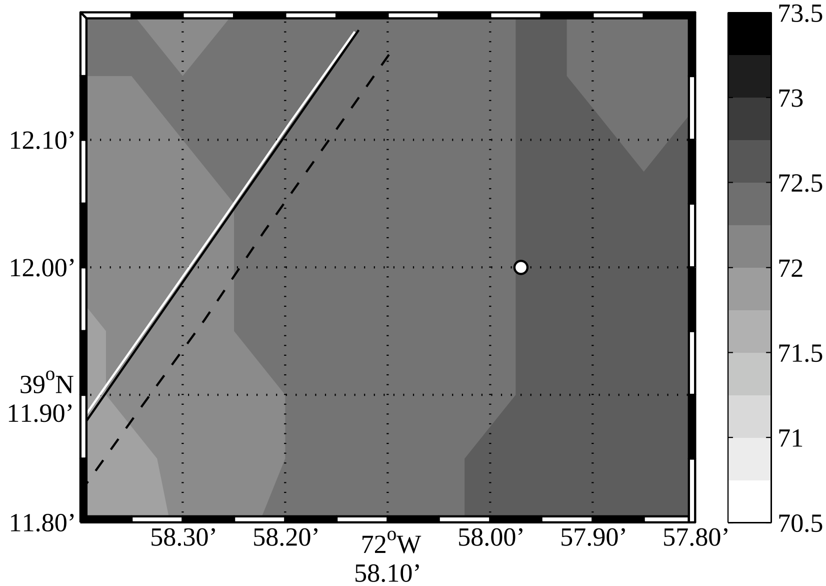

Figure 1: Shallow Water 2006 experimental location for part of sand ridge component showing three source tracks and location of receiving array (white circle).

For this analysis, on the basis of preexisting geophysical information[2-3], three candidate geoacoustic representations were selected. The first geoacoustic representation is an infinite halfspace. There are two unknown parameter values, the sound speed ratio R and the density ρ. The second representation is a two-layer model, where the first layer has a fixed sediment thickness of 25 meters and the second layer is an infinite halfspace. The choice of 25 meters reflects an average value for the depth of the R-reflector in the region of the array. In addition to the ratio and density, a sound speed gradient g_1 defines the first layer. The third representation is the same as the second representation except that the sediment thickness of the first layer is not fixed, and has an upper and lower bound of 1

and 50 meters, respectively. For all three representations, the sediment attenuation was assumed known from the previous analysis in ref. 4.

Figure 2 shows marginal distributions for three geoacoustic representations and four data elements. These distributions were obtained by integrating the canonical posterior probability distributions (PPD) over the nussiance parameters in the model space. In each case the number of Monte Carlo samples is 10^6. Convergence was checked by increasing the number of samples to 10^7. For the geoacoustic parameters the only parameter that is well resolved is the sound speed ratio at the water-sediment interface (R_1). This result is consistent with the preexisting geophysical data in ref. 5 that indicated the presence of a course sand at the surface of the seabed. One observes that for the third geoacoustic representation, there exists a *long tail* for the low ratio values in the marginal distribution for the R_1. The reason is that there is ambiguity between parameter values in the first and second layers for that section of the model space where the sediment thickness of the first layer is small. The low frequencies in the data are unable to resolve the sediment thickness, thus creating ambiguity in the sound speed ratio. This ambiguity is less for the second geoacoustic representation because the thick first sediment layer decouples the parameter values in the first and second sediment layers.

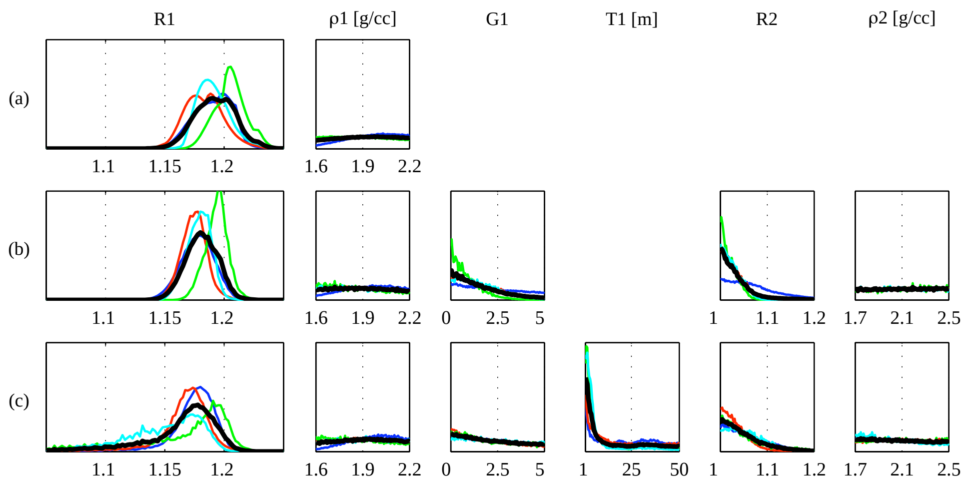

Figure 2: Marginal distributions using uniform sampling with 1 million samples. Rows (a), (b), and (c) correspond to environmental representations 1, 2, and 3 respectively. Colered curves are distributions that arise from the individual data samples. Black curve is the average marginal distributions for the four data samples.

Included in Fig. 2 is the average marginal distribution of the four data elements (black curve). Since each of the data elements are taken from the same statistical population, one should not attach a greater importance to a distribution derived from a specific data element, and thus it is logical to define uncertainty in terms of the average marginal distribution. Table I shows, for the average canonical distribution, the mean value and the standard deviation for both the sound speed ratio R and the sound speed C at the surface of the seabed, where $C = C_w R$ and the measured sound speed at the bottom of the water column is C_w =1497 m/s.

Table I: Sound speed ratio, sound speed, and standard deviations of first sediment layer derived from average marginal distributions for the three geoacoustic representations.

Seabed Representation	<R>	$\sigma_{<R>}$	<C> - m/s	$\sigma_{<C>}$ - m/s
1	1.1924	0.0172	1785.0	25.75
2	1.1811	0.0136	1768.1	20.36
3	1.163	0.0319	1741.0	47.75

The higher average sound speed for the first geoacoustic representation possibly suggests that the halfspace representation is an effective representation for higher speed layers beneath the water-sediment interface.

(2) Effect of subbottom layering

Figure 3 shows subbottom layering as a function of range along one of three propagation tracks examined in ref. 6. The layering structure was interpolated from seismic horizons interpreted from previously-collected chirp reflection data.[3]

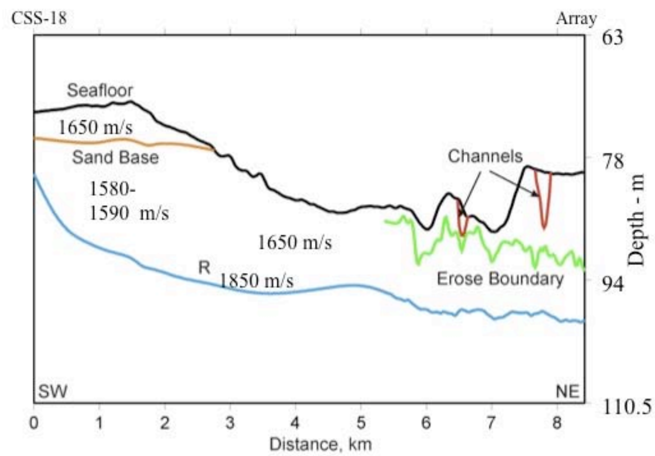

Figure 3: Measured bathymetry and seabed layering between CSS-18 and Array 3.

The source (CSS-18) is a combustive sound source event deployed in a position where the water depth was about 70 m. The water depth at the receiving array is about 79 m. As observed in Fig. 3, the water depth between the receiver and CSS-18 varies from about 70 to 86 m.

For the acoustic propagation from the CSS-18 source location to the array, the range is about 8.44 km (approximately 110 water depths). The source and receiver depths are about 26.2 and 79 m, respectively. Figure 4a shows the model-data comparison of the received time series in the 35-265 Hz band, and Fig. 4b shows the model-data comparison of the received time series in the 35-75 Hz band. Qualitatively, the modeled and the measured time series in both Figs. 4a and 4b agree. The time series in Fig. 4a and 4b exhibit a set of low-frequency modal arrivals, where a higher order mode follows a lower order mode. Figure 5a and 5b compare time series in the 35-265 and the 35-75 Hz band, respectively, simulated with the benchmark profile (Fig. 3) and with a modified geoacoustic structure. The modified geoacoustic structure is horizontally stratified and specified as the geoacoustic profile at the deployment location of CSS-18. Above about 75 Hz the range dependent layering in the benchmark geoacoustic profile had little effect on the simulated arrival structure as compared to the modified geoacoustic structure. Figure 5c shifts the simulated time series for the modified profile by about 10 ms relative to the simulated time series produced with the benchmark geoacoustic profile. Figure 5c clearly shows that the main effect of the range-dependent layering in the 35-75 Hz band is to increase the relative group velocity of the two modal arrivals.

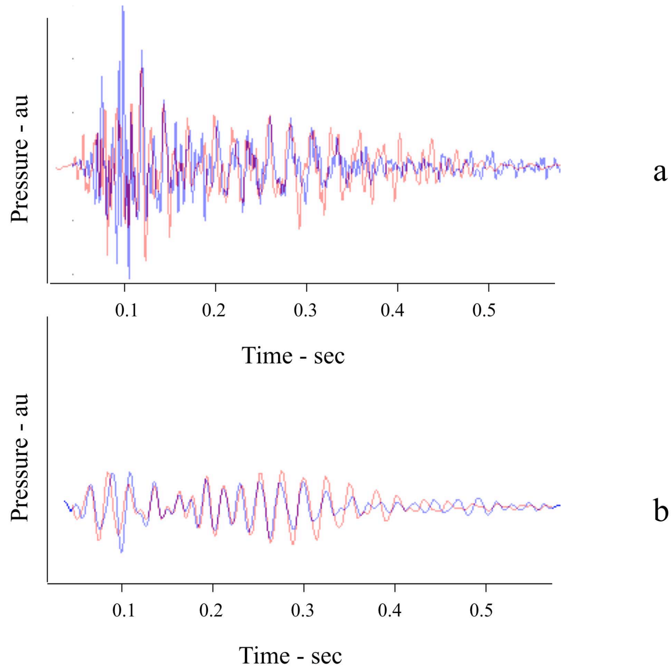

Figure 4: Model (red)-data (blue) comparison for CSS Event 18 at Array 3 for simulations with benchmark geoacoustic structure: (a) in 35-265 Hz band, (b) in 35-75 Hz band.

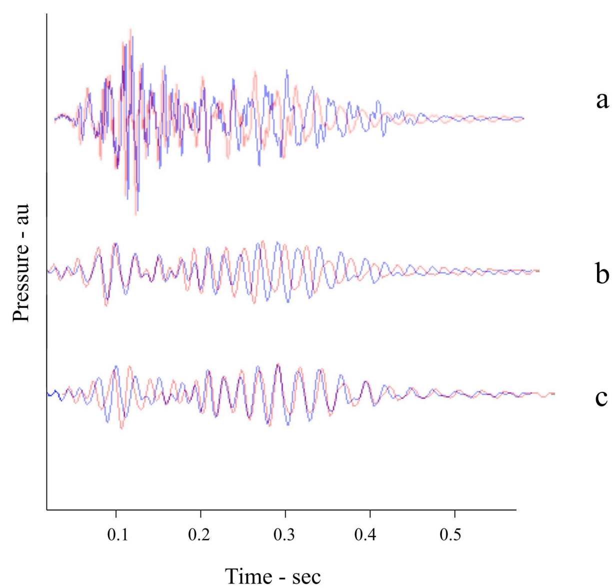

Figure 5: Comparison of CSS Event 18 at Array 3 simulations from modified (red) and benchmark (blue) geoacoustic structures in (a) 35-265 Hz band, (b) 35-75 Hz band, (c) 35-75 Hz band with 10 ms time shift of simulation with modified geoacoustic structure.

IMPACT/APPLICATIONS

One potential impact of this research is that these studies may assist in understanding how to optimally combine advance propagation models (non-separable and 3-D) and information inference methods as one proceeds to study ocean waveguides with increasing complexity and inhomogeneity.

TRANSITIONS

The maximum entropy approach has been transitioned to a sonar performance algorithm. The combined study of statistical inference and the effects of seabed layering is expected to lay a foundation for relating propagation statistics to physical mechanisms on continental shelf and slope environments. The knowledge of such statistics and their relationship to the physics of the propagation is viewed as Navy relevant for the important continental shelf and slope environment.

RELATED PROJECTS

Related research projects include modeling reverberation in range- and azimuth-dependent littoral areas and calculations of environmental and source uncertainty for acoustic data collected in experiments other than SW06.

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PUBLICATIONS

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HONORS/AWARDS/PRIZES

Became a Fellow of the Acoustical Society of America, Induction at November 2009 ASA meeting in Baltimore, MD.